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THE ORBITER AIR DATA SYSTEM

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ABSTRACT

Air data parameters are required during Orbiter atmospheric entry for use by the auto-guidance, navigation, and flight control systems, and for crew displays. Conventional aircraft calibrations of the Orbiter air data system were not practicable for the Space Shuttle, therefore extensive wind tunnel testing was required to give confidence in the preflight calibrations. Many challenges became apparent as the program developed; in the overall system design, in the wind tunnel testing program, in the implementation of the air data system calibration, and in the use of the flight data to modify the wind tunnel results. These challenges are discussed along with the methods used to solve the problems.

NOMENCLATURE

SYMBOLS

C_{P_s}	Static pressure coefficient
M	Mach number
P_C	Center port (pressure)
PL	Lower port (pressure)
PM	Measured static pressure
PS	Static pressure (port)
PT	Total pressure (port)
PU	Upper port (pressure)
$\bar{q}$	Dynamic pressure
T_T	Total temperature
X	Orbiter vehicle X-station
Y	Orbiter vehicle Y-station
α	Angle of attack
β	Angle of sideslip

SUBSCRIPTS

C	Calibration-corrected value
CAL	Calibration parameter value
m	Measurement by air data probe
WT	Wind tunnel
∞	Free-stream value

ACRONYMS

ADS	Air data system
ADTA	Air data transducer assembly
ALT	Approach and landing test
A/L	Approach and landing
ARC	Ames Research Center
FRL	Fuselage reference line
FS	Fuselage X-station
FTB	Flight test boom (flight test probe and mast)
GN&C	Guidance, navigation and control
GPC	General purpose computer
IMU	Inertial measurement unit
LaRC	Langley Research Center
LeRC	Lewis Research Center
MS	Model X-station

NAAL	North American Aerodynamics Laboratory
NASA	National Aeronautics and Space Administration
OA	Orbiter aerodynamics test series
OFT	Orbital flight test
OML	Outer mold line
STS-1	First space transportation system flight (OFT)
TAEM	Terminal area energy management
TPS	Thermal protection system
WL	Fuselage water line
WP	Fuselage water plane

INTRODUCTION

The NASA Space Shuttle is designed as a reusable transportation system to near Earth orbit. The prime element of the total Space Shuttle configuration is the payload - carrying Orbiter. Subsequent to launch and orbital operations the Orbiter must be able to negotiate the critical entry portion of the flight and land safely on a conventional runway. During the entry phase, the Orbiter configuration must maintain stability and control as well as a required trim attitude, for large center of gravity position changes and a large angle of attack span (the latter from heating and ranging considerations). Mach number varies from 28 at initial entry to approximately 0.25 at landing, and the angle of attack varies from 40 degrees to 0 degrees. During entry to touchdown, the automatic flight control system passes through three distinct phases: entry, terminal area energy management (TAEM) and approach and landing (A/L). Each of these phases has established requirements for processed air data, such as angle of attack, altitude, Mach number, etc., from the Orbiter air data system (ADS) for the conditions shown in table I.

In many ways, the Orbiter ADS is a typical ADS. It uses two fuselage-mounted probes to measure local flow conditions. Freestream conditions, such as Mach number, angle of attack, and altitude are computed using previously derived calibration algorithms. The freestream conditions are used by the guidance, navigation and control (GN&C) system and are also displayed to the crew. In addition, air data are used extensively during the postflight aerodynamic analyses.

In terms of obtaining accurate preflight air data calibrations for the Orbiter there existed a somewhat unique situation. The typical aircraft flight calibration was not practicable (i.e. tower flyby, pacer aircraft, etc. type testing was not compatible with any sustained Orbiter test flight conditions). In addition, the blunt nose of the Orbiter causes large "position errors" that must be accounted for in the calibration. Because of all the aforementioned conditions, an extensive wind tunnel calibration program was required. The approach and landing test (ALT) phase of the flight test program had a conventional flight test boom (FTB) installed in the nose of the Orbiter for the purpose of evaluating the subsonic wind tunnel calibration of the ADS. The wind tunnel data were merged with data obtained during the ALT program to produce an on-board calibration for orbital flight test (OFT) and a more accurate calibration for the postflight aerodynamic analyses. Results from the OFT program indicated that the on-board calibration easily met the specified requirements. These results were also used in an extensive effort to refine the postflight calibration in order to provide the best possible data for the postflight aerodynamic analyses.

SYSTEM DESCRIPTION

A sketch of the Orbiter ADS probes illustrating their location on the Orbiter nose is shown in figure 1. There are two probes, one on either side of the vehicle. They are secured to rotating doors that allow them to be stowed (and thus protected) during ascent, orbit, and initial re-entry. The probes are deployed during re-entry when the Orbiter has slowed to approximately Mach 3.5. Each probe includes a semispherical head with three pressure measurements. The center port (P_C) gives an indication of total pressure (P_{T_m}), and senses local total pressure when the probe is aligned with the local flowfield. The upper and lower ports (P_U and P_L) are sensitive to local flow angle. In addition, several static pressure ports (P_{S_m}) are located aft on the probe shaft, and a total temperature (T_T) sensor is located at the rear. The probes are connected to four air data transducer assemblies (ADTA's), redundant pairs per side, through pneumatic lines. The ADTA's house pressure transducers that convert the probe-measured pressures to electrical signals. Using the ADS calibrations, the general purpose computer (GPC) processes the ADTA signals to provide the basic air data parameters: static pressure, total pressure, and angle of attack. From these basic parameters, Mach number, dynamic pressure, pressure altitude, equivalent airspeed, and true airspeed are computed.

The ADS calibration relates a set of conditions that cannot be measured directly during flight (i.e., Mach number, angle of attack, etc.) to a set of parameters that can be measured (i.e., probe total, static, upper and lower pressures, and total temperature). In the wind tunnel, specific freestream conditions (i.e., static and total pressure, angle of attack, and Mach number) are known to a relatively high degree of accuracy. During a wind tunnel test these conditions are held constant, while the probe pressures are carefully measured and recorded. A schematic depicting the relationship between wind tunnel and flight measurements/calibration is shown in figure 2. The flight probe measurements are channeled through the calibration software to calculate the air data parameters as shown in figure 3.

Some of the more obvious "system" challenges for the Orbiter ADS were deployment/storage capability and system redundancy. A definition of when ADS deployment would occur depended on a trade between the high heat environment that occurs early in re-entry and where ADS information is needed to increase the GN&C system performance levels. From heating information and entry simulations a value near Mach 3.5 was agreed on. In actual practice the ADS parameters are computed in the GPC, compared with other available sources, as well as with the redundant air data sources, then if deemed good data, used at Mach 2.5 and below.

Redundancy was built into the system by having two probes (right and left) and two separate ADTA's for each pressure measurement. Because of this redundancy four sets of air data parameters were produced and a rating system was used for selection of the "best" data. A more detailed assessment of the ADS estimated performance and the system definition can be found in references 1 and 2.

WIND TUNNEL TEST PROGRAM

The ADS wind tunnel calibration development program initially consisted of one low subsonic calibration test of a complete 0.36 scale Orbiter with 0.36 scale side probes; one transonic test, one low supersonic test, and one high supersonic test of a 0.10 scale forebody model with 0.20 scale side probes. Because of physical size limitations, for the transonic and supersonic tests the smallest side probes that could be tested with at least pitot-static instrumentation or upper and lower pressure instrumentation in each probe, was 0.20 scale. The largest model size that could be tested without introducing significant blockage was 0.10 scale, resulting in a model-scale, probe-scale difference. Due to test data problems related to the scale difference the wind tunnel test program was expanded in the Orbiter aerodynamics (OA) series to that shown in table II.

Prior to wind tunnel model design and testing philosophy many compromises had to be decided upon. The full-scale Orbiter vehicle is over 107 feet long and the side probes are approximately 1 foot long. Testing facilities have model size constraints that were pushed to the limit. There were no model scaling problems with the 0.36 scale Orbiter. There were however, problems retaining the configuration fidelity on the 0.10 scale forebody model. In this case the model had to be shortened and was boat-tailed in the region of fuselage station 670 (full-scale) as shown in figure 4. In addition, as previously mentioned, the side probes were 0.20 scale in order to get two of the four pressure lines in one side probe (for PU and PL), and two in the other probe (for PS and PT). As much geometric similarity as possible was retained in the region of the side probes. For determining probe scale effects, the static pressure port standoff distance (Y_{PS}) and X-model station location (X_{PS}) were correctly simulated. For total pressure and angle of attack measurements, the 0.20 scale probe was moved aft such that the probe tip X-station corresponded to a 0.10 scale probe tip X-station. Further model/configuration duplication problems resulted because only a portion of the wing root could be retained. The effects of all of these model/full-scale vehicle differences on the probe measurements were investigated. In addition, differences in the vehicle outer mold line (OML) between the initial lines and the final configuration lines were assessed. The solution to these model scale and model fidelity problems was to use theoretical calculations where possible and run supplementary tests otherwise. Potential flow calculations were used to determine the effects of afterbody closure (boat-tail), model/probe scale mismatch, and OML duplication. Effects of the wing root/leading edge exclusion was measured in test OA-22. The results, in the form of pressure increments, were added to the basic data and an estimated uncertainty added in the accuracy analysis.

Data problems that resulted later during the actual testing were: facility reference static pressure differences, effects of model/probe scale mismatch (for the 0.10 scale forebody model), OML differences, and wind tunnel blockage effects. Facility reference conditions are dependent on when and how each facility performs their calibrations. The reference conditions were investigated by testing several standards and calibration devices that were available and comparing these with a slender cone-cylinder probe furnished by the manufacturer of the side probes. The results indicated differences from the reference probe from +1.0 percent to -1.5

percent of $\bar{q}$. During the later ascent air data system wind tunnel calibration program similar procedures were used.[3] These corrections were applied to all data used in subsequent analyses. The effect of model/probe scale mismatch (subsonically) is detailed in reference 2. Basically a larger effect was found from that estimated earlier by the theory, particularly at angles of attack where the theory assumes zero angle of attack. The effect of OML changes is also delineated in reference 2. Here, because of quite drastic configuration modifications in the nose area a new 0.10 scale forebody was constructed. Blockage effects were also determined by testing. Test OA237 was conducted using the smaller (0.10) scale model and the results were compared to the larger (0.36) scale model that was tested previously is this same facility. All of these aforementioned testing problems are discussed in more detail in reference 4.

CALIBRATION FORMULATION/IMPLEMENTATION

The development of the ADS calibration involved deriving a set of calibration parameters that relate the freestream conditions to the probe-measured conditions, using the wind tunnel derived data base. From the freestream conditions, the various air data parameters (Mach number, altitude, etc.) can be computed using basic aerodynamic equations. Analysis of the static pressure coefficient with Mach number indicated a "Mach Jump" region of extremely non-linear data. As the free stream Mach number increases to 1.0 and greater, a bow shock is formed that stands off the Orbiter nose. The bow shock delays the local Mach number at the side probe from reaching sonic speeds until the free-stream Mach number is in the range of 1.2 to 1.4. When the local flow reaches sonic speeds a very large rise in measured static pressure occurs and is referred to as the static pressure "Mach Jump". Figure 5 shows the variability of static pressure coefficient with Mach number. To avoid the extreme non-linearities in the onboard software implementation, static pressure is derived from a GPC stored standard atmosphere model for Mach numbers from 0.9 to 1.6.

Analyses of the wind tunnel data calibration parameters resulted in a set of polynomial equations with over 600 coefficients. For the on-board calibration, software storage limitations dictated 200 or less coefficients. Studies to reduce the number of coefficients indicated that by fitting the polynomials to concentrate on nominal trajectory conditions the number of coefficients could be reduced to 196.

Another potential error source was the on-board initialization of the calibration. The system begins with the previous Mach number (initially an assumed Mach number) to enter the calibration equations, but does not iterate with a corrected Mach number. Prior to STS-1, it was analytically shown that the rate of change of Mach number, and/or the calibration coefficients, was low enough to preclude a significant error. This analysis has been verified by flight results.

FLIGHT DATA ANALYSES

Post flight data from the ALT series were used to adjust the ADS calibrations in the subsonic flight regime. Data from the OFT series was used to adjust the ADS calibrations at the higher Mach numbers, where much smaller modifications were required.

APPROACH AND LANDING FLIGHT DATA

The ALT phase of the flight test program had a conventional flight test boom (FTB) installed in the nose of the Orbiter for the purpose of evaluating the subsonic wind tunnel calibration of the ADS using data from the FTB as a reference. In addition to FTB data, ground data in the form of radar and phototheodolite tracking, combined with weather balloon data, were used to verify the FTB. In order that the FTB data be used to correct the wind tunnel data, all potential sources of error had to be eliminated or accounted for. Adjustments and compensations were made to the FTB attitude data for the following effects: aerodynamic flowfield upwash and offset, FTB incidence and mounting misalignment, change in the aerodynamic flowfield due to vehicle pitch rate, and FTB structural deflections due to normal acceleration, pitch acceleration, and airloads. Pressure coefficients from the FTB were seen to be very accurate, with no calibration required for total pressure and only small adjustments for static pressure. The resulting flight data from the ALT series was used with the transonic and supersonic wind tunnel data to formulate the calibration for the OFT series.[5]

ORBITAL FLIGHT TEST DATA

The ADS calibration for OFT proved to be adequate for on-board use (see table I). For post-flight aerodynamic analysis, however, further refinements were developed from the flight programs to produce the best possible air data parameters for postflight analysis work. From Mach 3.5 to Mach 0.6, the meteorological static pressure was substituted for that derived by the ADS. From Mach 0.6 to landing gear deployment, corrections derived from a regression analysis technique were applied to angle of attack, static pressure, and total pressure. The resulting ADS calibration has generated air data that has been used in conjunction with flight-derived aerodynamic data to evaluate the performance of the Orbiter during re-entry.[6]

SUMMARY

The Shuttle ADS calibration was difficult to obtain because of the Orbiter unique flight regime, configuration, and operational characteristics. System challenges involved when to deploy the ADS probes to avoid reentry heating and how to handle the ADS redundancy requirement. During the wind tunnel calibration data discrepancies surfaced, with the major problems identified as: facility reference pressure, model/probe scale differences, OML changes and blockage effects. Calibration implementation challenges were "Mach Jump", on-board software limitations and air data calculation initialization. Each of these problems was surmounted by careful analysis of the existing data and by thorough design of supplementary testing to resolve the data discrepancies. Testing hardware and techniques were modified for on-going testing as required. The resulting preflight calibrations were modified using the ALT data (subsonic flight) to formulate the OFT calibration. Post-flight comparisons of OFT data showed the calibration to be adequate for operational flight. Further refinements were made, however, to assist in the evaluation of the aerodynamic characteristics of the Orbiter.

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Table I. Orbiter Air Data System Parameter Requirements.

AIR DATA PARAMETER	SYMBOL	UNITS	FLIGHT PHASE UTILIZATION	SYSTEM REQUIREMENT RANGE	SYSTEM REQUIREMENT ACCURACY (% OF READING UNLESS NOTED) (3σ)	CREW DISPLAY
GEODETIC ALTITUDE (PRESSURE ALTITUDE CORRECTED FOR NON-STANDARD ATMOSPHERE)	h_{pc}	FT	ENTRY & TAEM	10K TO 100K	±10%	YES
PRESSURE ALTITUDE RATE (SINGLE PROBE OPERATION ONLY)	$\dot{h}$	FPS	TAEM A/L	0 TO -600 0 TO -250	±10 FPS OR ±5% W/E IS GREATER ±2 FPS OR ±5% W/E IS GREATER	YES
DYNAMIC PRESSURE	$\bar{q}$	PSF	TAEM & A/L	90 TO 375	±10%	NO
MACH NUMBER	M	—	TAEM A/L	0.6 TO 2.5 0.25 TO 0.6	±10% ±10%	YES
TRUE AIRSPEED	V_T	FPS	TAEM A/L	600 TO 2500 250 TO 600	±10% ±10%	NO
EQUIVALENT AIRSPEED	V_e	KTS FPS	TAEM & A/L A/L	160 TO 335 112 TO 270	±5% ±5%	YES
ANGLE OF ATTACK	α	DEG	TAEM & A/L	-4 TO +20	±2°	YES

Table II. Orbiter Air Data System Wind Tunnel Program

TEST	MODEL SCALE		MACH RANGE	FACILITY	PURPOSE
	ORBITER	PROBE			
OA-22	0.03	None	0.6 → 1.5	ARC 11x11, 9x7	Pressure survey
OA-143	0.03	None	0.25	Rockwell NAAL	Pressure survey
OA-100	0.36	0.36, FTB	0.25	ARC 40x80	Development
OA-164	0.36	0.36, FTB	0.25	ARC 40x80	Development (Contd.)
OA174	0.36	0.36	0.25	ARC 40x80	Verification
OA-161A,B,C	0.03	None	0.6 → 3.5	ARC 11x11, 9x7, 8x7	Pressure and local survey
OA-220	0.10 (forebody)	0.20, FTB	0.3 → 1.1	ARC 14x14	Development
OA-224	0.10 (forebody)	0.20	0.2 → 1.3	LaRC 16-ft transonic	Verification
OA-228	0.10 (forebody)	0.20	0.25	Rockwell NAAL	Static pressure comparison
OA-237	0.10 (forebody)	0.10, 0.20	0.25	ARC 40x80	Scale and blockage
OA-232	0.10 (forebody)	0.10, 0.20	0.2 → 1.3	AEDC 16T	Scale and blockage
OA221B,C	0.10 (forebody)	0.20	1.5 → 3.5	ARC 9x7, 8x7	Development
OA-234	0.10 (forebody)	0.10, 0.20	2.0 → 3.5	LeRC 10x10	Verification
OA-238	0.10 (forebody)	0.10	0.25	Rockwell NAAL	Scaled probes
OA-251B,C	0.10 (forebody)	0.10, 0.20	1.5 → 3.5	ARC 9x7, 8x7	Verification
Other tests:					
OA-236	Tunnel Calib. Probes		0.25	Rockwell NAAL	Facilities calibration comparison

ARC=Ames Research Center, NAAL=North American Aero. Lab., LaRC=Langley Research Center, LeRC=Lewis Research Center

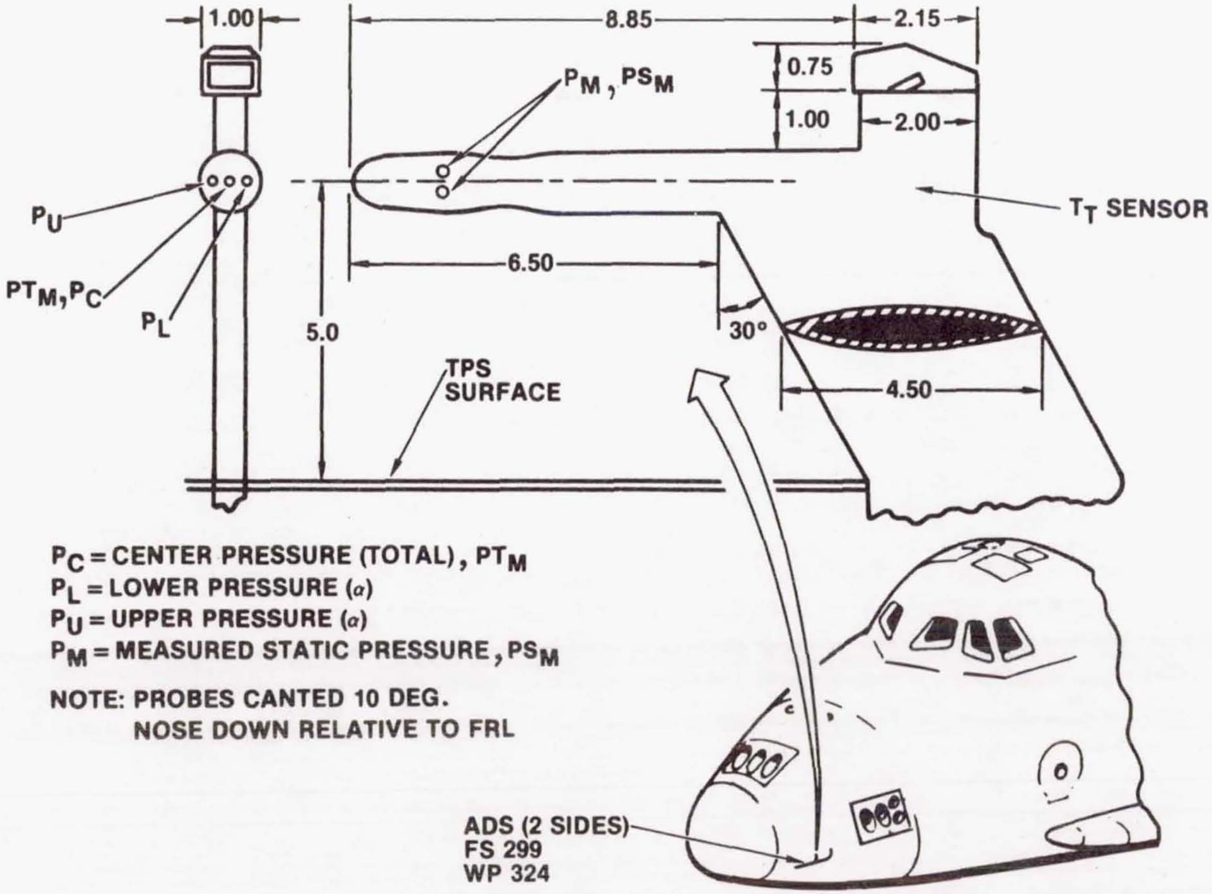

Fig. 1 Orbiter ADS Probe Geometry (All Measurements In Inches)

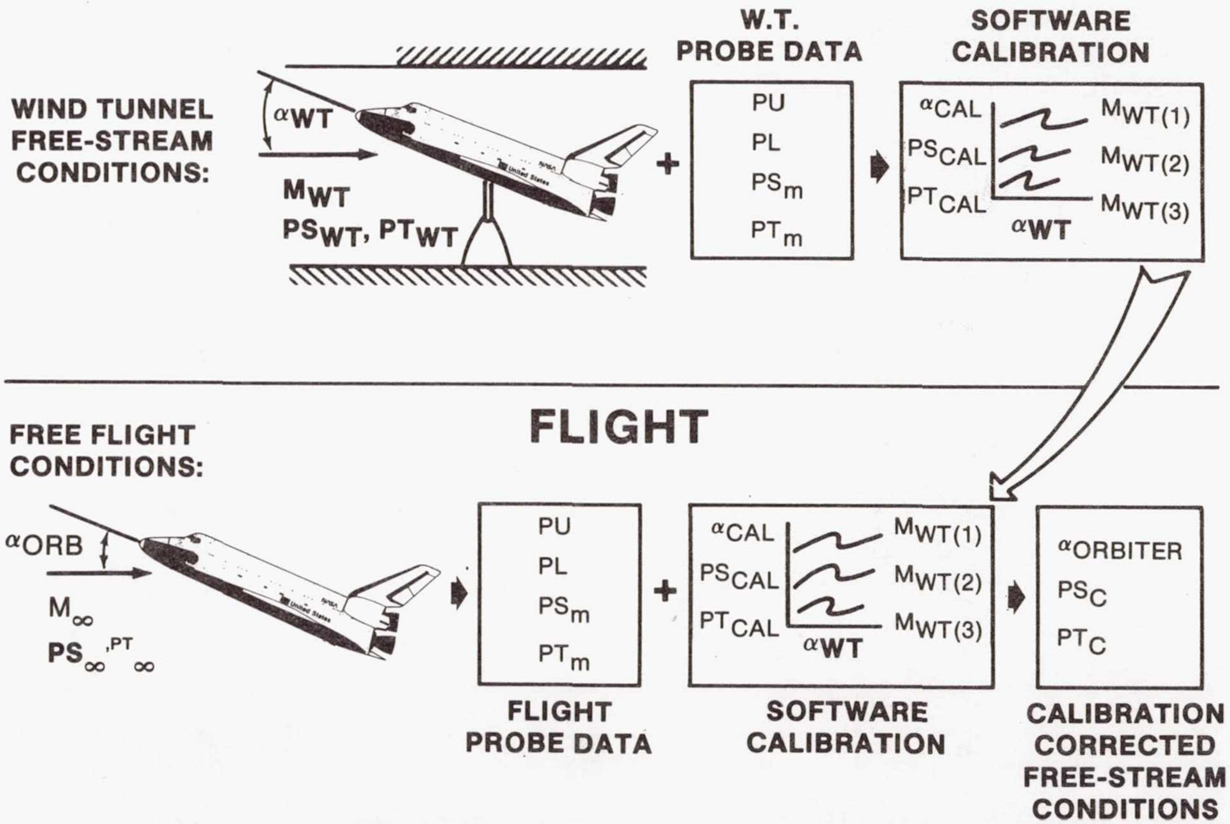

Fig. 2 Wind Tunnel ADS Calibration/Flight Usage

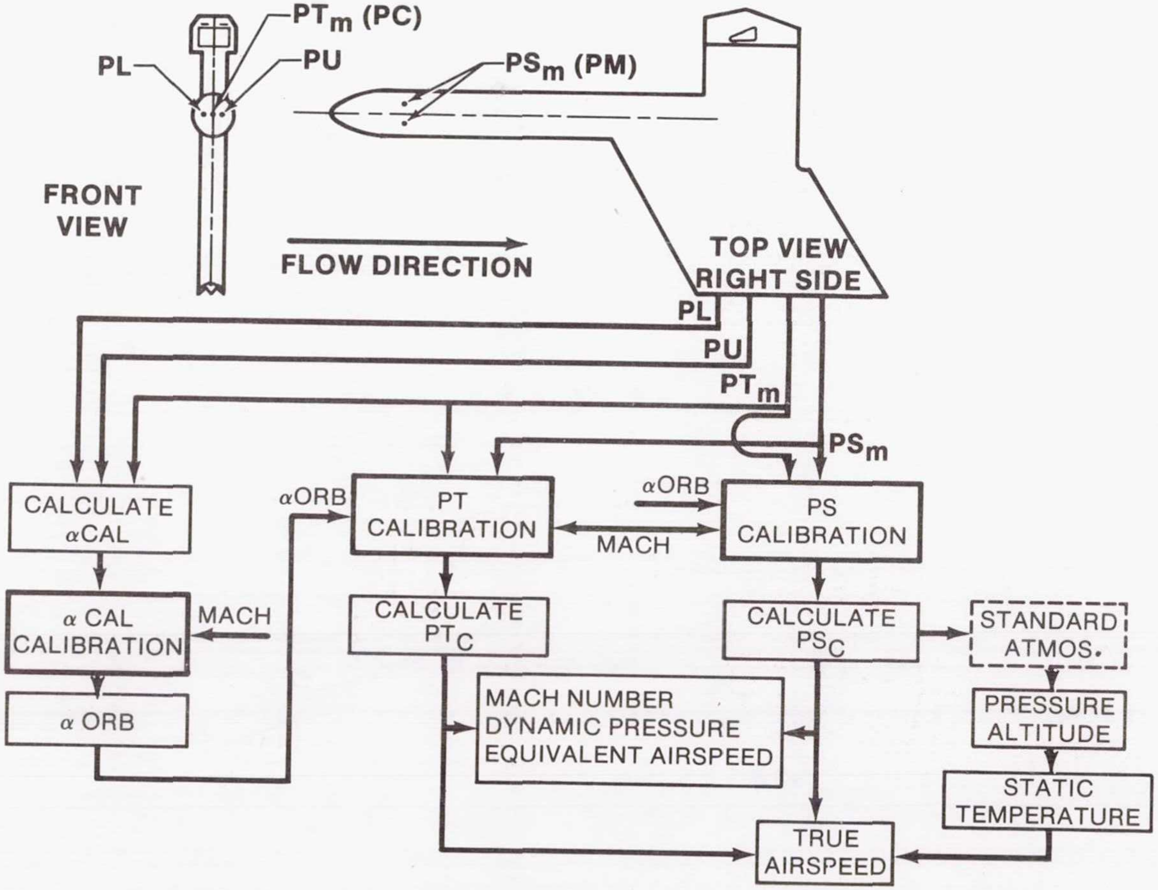

Fig. 3 Operational ADS Software Calculations

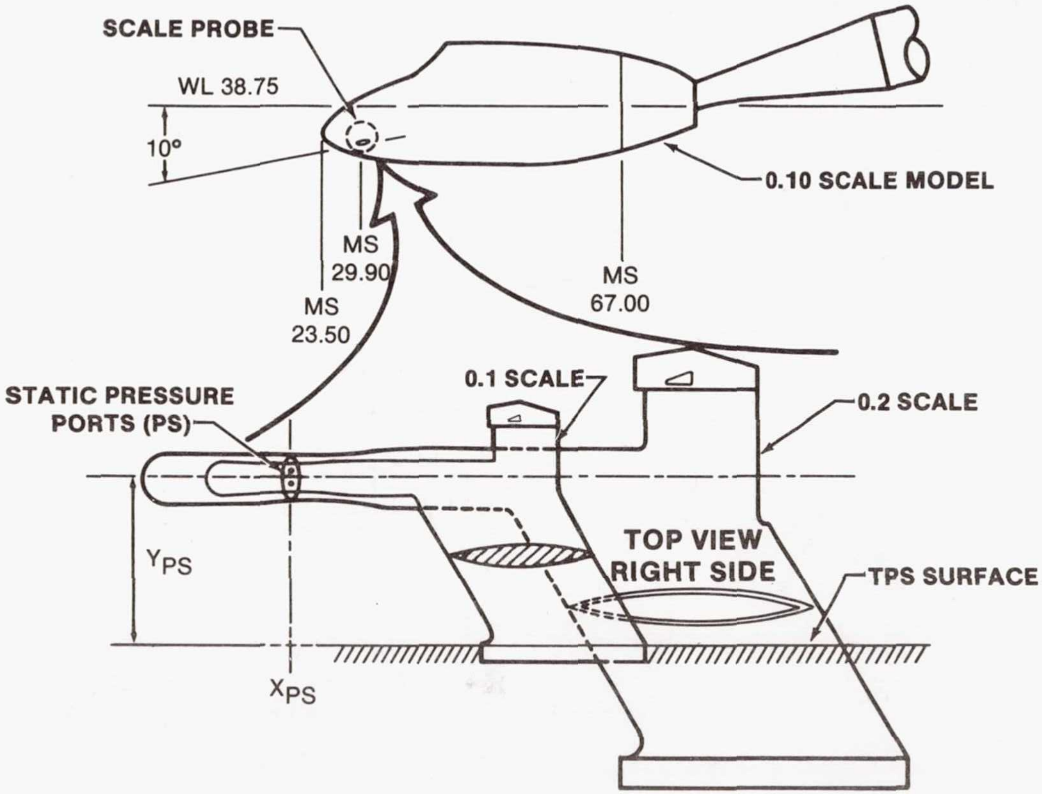

Fig. 4 Side Probe/Model Scaling Compromises

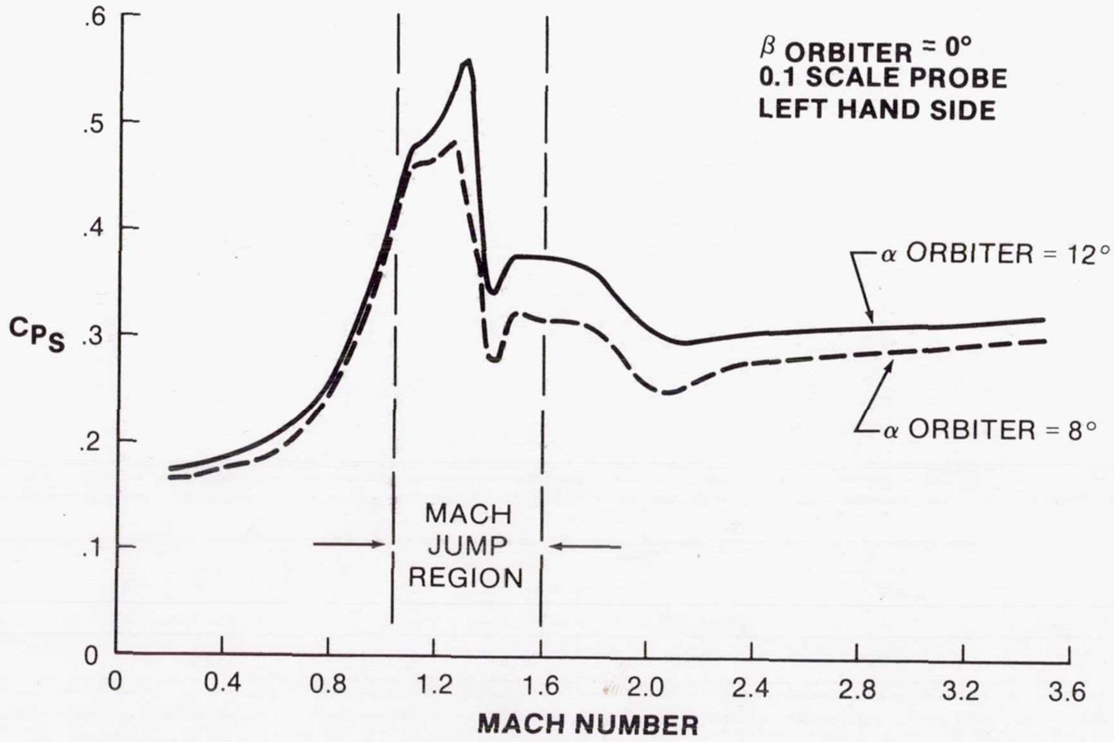

Fig. 5 Variation of Static Pressure Coefficient with Mach Number